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Narrow Technihadron Production at the First Muon Collider

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Abstract

In modern technicolor models, there exist very narrow spin-zero and spin-one neutral technihadrons—π_T^0, ρ_T^0 and ω_T—with masses of a few 100 GeV. The large coupling of π_T^0 to $\mu^+\mu^-$, the direct coupling of ρ_T^0 and ω_T to the photon and Z^0, and the superb energy resolution of the First Muon Collider may make it possible to resolve these technihadrons and produce them at extraordinarily large rates.

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The next big step in collider physics after the Large Hadron Collider is a matter of great importance and considerable debate. Electron-positron linear colliders with center-of-mass energy $\sqrt{s} = 500$–$1000\,\mathrm{GeV}$ are touted for the clean environment of their interaction region and high signal-to-background rates. Hadron colliders, with pp or $\bar{p}p$ beams, can make a substantial leap beyond the LHC with $\sqrt{s} \gtrsim 100\,\mathrm{TeV}$ and integrated luminosities exceeding $100\,\mathrm{fb}^{-1}$ per year (hence subprocess energies exceeding $10\,\mathrm{TeV}$). The proponents of $\mu^+\mu^-$ colliders claim they can deliver the the best aspects of both: relatively clean and background-free collisions (at least for $|\cos\theta| \lesssim 0.95$) and very high collision energies, in the range 2–4 TeV. However, the potential difficulties of a muon collider are so great that a successful low-energy prototype, the First Muon Collider (FMC) with $\sqrt{s} = 100$–$500\,\mathrm{GeV}$, certainly must be demonstrated.

So far, the primary justification for a low-energy muon collider has been copious resonant production of neutral Higgs bosons, H^0, such as expected in minimal or multi-Higgs doublet standard models or their supersymmetric variants. Because the H^0 coupling to $\mu^+\mu^-$ is of order m_μ/v, where $v = 246\,\mathrm{GeV}$, the Higgs cross section is $(m_\mu/m_e)^2 = 10^4$ times greater in the FMC than it is in an e^+e^- collider. Furthermore, the beam momentum resolution claimed for the FMC, $\delta p/p = 10^{-5}$–10^{-3} [1], is much better than can be achieved in linear e^+e^- colliders, making $\mu^+\mu^-$ production rates even larger. Although neutral Higgs bosons will be discovered at the Tevatron or LHC, the advantages that a muon collider has over a hadron collider for studying the details of H^0 production and decay are obvious.

In this letter we point out another strong motivation for the First Muon Collider: Modern technicolor models, particularly topcolor-assisted technicolor (TC2) [2] with a walking gauge coupling [3], are expected to contain many technihadron states, some lying at the low energies the FMC will probe. These states, specifically, neutral technipions and technivectors, are very narrow and can be produced as s-channel resonances in $\mu^+\mu^-$ annihilation. The cross sections on resonance are enormous—from 1/10 to 10 nanobarns. The energy resolution of the FMC permits a substantial part of these peak production rates to be realized. In no other machine can such precise and spectactular studies of low-mass technihadrons be executed. [1]

[1]The lightest technihadrons should be accessible at the Tevatron collider in Run II or III [4]. They are easily produced and detected at the LHC at moderate luminosities.

We assume that the technicolor gauge group is $SU(N_{TC})$ and take $N_{TC} = 4$ in calculations. Its walking gauge coupling is achieved by a large number of isodoublets of technifermions transforming according to the fundamental representation of $SU(N_{TC})$. We consider the phenomenology of only the lightest color-singlet, spin-zero and one technihadrons and assume that they may be considered in isolation for a *limited* range of the $\mu^+\mu^-$ energy $\sqrt{s}$ about their masses. [2] These technihadrons consist of a single isotriplet and isosinglet of vectors, ρ_T^0, $\rho_T^\pm$ and ω_T, and pseudoscalars π_T^0, $\pi_T^\pm$, and $\pi_T^{0\prime}$. The latter are in addition to the longitudinal weak bosons, $W_L^\pm$ and Z_L^0, which are technipion bound states of all the technifermions. In TC2 there is no need for large technifermion isospin splitting associated with the top-bottom mass difference. Thus, the lightest ρ_T and ω_T are approximately degenerate. The lightest charged and neutral technipions also should have roughly the same mass, but there may be appreciable π_T^0–$\pi_T^{0\prime}$ mixing. If that happens, the lightest neutral technipions are really techni-$\bar{U}U$ and $\bar{D}D$ bound states. Finally, for purposes of discussing signals at the FMC, we take the lightest technihadron masses to be $M_{\rho_T} \cong M_{\omega_T} \sim 200\,\mathrm{GeV}$; $M_{\pi_T} \sim 100\,\mathrm{GeV}$.

Technipion decays are induced mainly by extended technicolor (ETC) interactions which couple them to quarks and leptons [8]. These couplings are Higgs-like, and so technipions are expected to decay into the heaviest fermion pairs allowed. In TC2, only a few GeV of the top-quark's mass is generated by ETC, so there is no great preference for π_T to decay to top quarks nor for top quarks to decay into them. Furthermore, the isosinglet component of neutral technipions may decay into a pair of gluons if its constituent technifermions are colored. Thus, the decay modes of interest to us are $\pi_T^0 \to \bar{b}b$ and, perhaps $\bar{c}c, \tau^+\tau^-$, and $\pi_T^{0\prime} \to gg$, $\bar{b}b$. Branching ratios are estimated from (for later use in the technihadron production cross sections, we quote the energy-dependent widths [9, 10]):

$$\begin{aligned}
\Gamma(\pi_T \to \bar{f}'f) &= \frac{1}{16\pi F_T^2}\, N_f\, p_f\, C_f^2 (m_f + m_{f'})^2 \\
\Gamma(\pi_T^{0\prime} \to gg) &= \frac{1}{128\pi^3 F_T^2}\, \alpha_S^2\, C_{\pi_T}\, N_{TC}^2\, s^{\frac{3}{2}}\,.
\end{aligned} \tag{1}$$

[2] Technicolor models with QCD-like dynamics are incompatible with precision electroweak measurements [5], but these proofs are inapplicable to walking technicolor, principally because the electroweak spectral functions cannot be saturated by a single vector and axial vector resonance [6]. Also see Ref. [7].

Here, C_f is an ETC-model dependent factor of order one *except* that TC2 suggests $|C_t| \lesssim m_b/m_t$; N_f is the number of colors of fermion f; p_f is the fermion momentum; α_S is the QCD coupling evaluated at M_{π_T}; and C_{π_T} is a Clebsch of order one. We take $M_{\pi_T} = 110\,\mathrm{GeV}$, $F_T \equiv F_\pi/3 = 82\,\mathrm{GeV}$ for the technipion decay constant (for nine isodoublets of technifermions), $m_b = 4.2\,\mathrm{GeV}$, $\alpha_S = 0.1$, $C_b = 1$ for π_T^0 and $\pi_T^{0\prime}$, and $C_{\pi_T} = 4/3$. Then, the technipion partial widths are $\Gamma(\pi_T^0 \to \bar b b) = \Gamma(\pi_T^{0\prime} \to \bar b b) = 35\,\mathrm{MeV}$ and $\Gamma(\pi_T^{0\prime} \to gg) = 10\,\mathrm{MeV}$, quite narrow indeed.

As discussed in Refs. [11, 4], the standard two and three technipion decay channels of the lightest ρ_T^0 and ω_T probably are energetically forbidden. Then ρ_T^0 decays to $W_L^+ W_L^-$ or $W_L^\pm \pi_T^\mp$ and ω_T to $\gamma \pi_T^0$ or $Z^0 \pi_T^0$. We parameterized this for ρ_T decays with a simple model of two isotriplets of technipions which are mixtures of $W_L^\pm$, Z_L^0 and mass-eigenstate technipions $\pi_T^\pm$, π_T^0. The lighter isotriplet ρ_T is assumed to decay dominantly into pairs of the mixed state of isotriplets $|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$, where $\sin\chi = F_T/F_\pi$. Then,

$$\Gamma(\rho_T^0 \to \pi_A^+ \pi_B^-) = \frac{2\alpha_{\rho_T} \mathcal{C}_{AB}^2}{3} \, \frac{p_{AB}^3}{s} \,, \tag{2}$$

where p_{AB} is the technipion momentum and α_{ρ_T} is obtained by *naive* scaling from the QCD coupling for $\rho \to \pi\pi$, $\alpha_{\rho_T} = 2.91\,(3/N_{TC})$. The parameter $\mathcal{C}_{AB}^2 = \sin^4\chi$ for $W_L^+ W_L^-$, $\sin^2\chi\,\cos^2\chi$ for $W_L^\pm \pi_T^\mp$, etc. The ρ_T can be very narrow: For $M_{\rho_T} = 210\,\mathrm{GeV}$, $M_{\pi_T} = 110\,\mathrm{GeV}$, and $\sin\chi = \frac{1}{3}$, we have $\sum_{AB} \Gamma(\rho_T^0 \to \pi_A^+ \pi_B^-) = 680\,\mathrm{MeV}$, 80% of which is $W_L^\pm \pi_T^\mp$.

We shall also need the decay rates of the ρ_T to fermion-antifermion states. These proceed through the ρ_T^0 coupling to γ and Z^0:

$$\Gamma(\rho_T^0 \to \bar f_i f_i) = \frac{N_f\,\alpha^2}{3\alpha_{\rho_T}} \, \frac{p_i\,(s + 2m_i^2)}{s} \, A_i^0(s) \,. \tag{3}$$

Here, α is the fine-structure constant, p_i is the momentum and m_i the mass of fermion f_i, and

$$\begin{aligned}
A_i^0(s) &= |\mathcal{A}_{iL}(s)|^2 + |\mathcal{A}_{iR}(s)|^2 \,, \\
\mathcal{A}_{i\lambda}(s) &= Q_i + \frac{2\cos 2\theta_W}{\sin^2 2\theta_W}\, \zeta_{i\lambda} \left(\frac{s}{s - M_Z^2 + i\sqrt{s}\,\Gamma_Z} \right) , \\
\zeta_{iL} &= T_{3i} - Q_i \sin^2\theta_W ; \qquad \zeta_{iR} = -Q_i \sin^2\theta_W \,.
\end{aligned} \tag{4}$$

For parameters as above, the $\bar{f}f$ partial decay widths are 5.8 MeV ($\bar{u}_i u_i$), 4.1 MeV ($\bar{d}_i d_i$), 0.9 MeV ($\bar{\nu}_i \nu_i$), and 2.6 MeV ($\ell_i^+ \ell_i^-$).

For the ω_T, phase space considerations suggest we consider only its $\gamma \pi_T^0$ and fermionic decay modes. The energy-dependent widths are:

$$
\begin{aligned}
\Gamma(\omega_T \to \gamma \pi_T^0) &= \frac{\alpha p^3}{3 M_T^2}\,, \\
\Gamma(\omega_T \to \bar{f}_i f_i) &= \frac{N_f\, \alpha^2}{3 \alpha_{\rho_T}} \frac{p_i\,(s + 2m_i^2)}{s}\, B_i^0(s)\,. \qquad (5)
\end{aligned}
$$

The mass parameter M_T in the $\omega_T \to \gamma \pi_T^0$ rate is unknown *a priori*; naive scaling from the QCD decay, $\omega \to \gamma \pi^0$, suggests it is several 100 GeV. The factor $B_i^0 = |\mathcal{B}_{iL}|^2 + |\mathcal{B}_{iR}|^2$, where

$$
\begin{aligned}
\mathcal{B}_{i\lambda}(s) &= \left[Q_i - \frac{4 \sin^2\theta_W}{\sin^2 2\theta_W}\, \zeta_{i\lambda} \left(\frac{s}{s - M_Z^2 + i\sqrt{s}\,\Gamma_Z} \right) \right] \\
&\quad \times (Q_U + Q_D)\,. \qquad (6)
\end{aligned}
$$

Here, Q_U and $Q_D = Q_U - 1$ are the electric charges of the ω_T's constituent technifermions. For $M_{\omega_T} = 210\,\mathrm{GeV}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$, and choosing $M_T = 100\,\mathrm{GeV}$ and $Q_U = Q_D + 1 = \frac{4}{3}$, the ω_T partial widths are 115 MeV ($\gamma \pi_T^0$), 6.8 MeV ($\bar{u}_i u_i$), 2.6 MeV ($\bar{d}_i d_i$), 1.7 MeV ($\bar{\nu}_i \nu_i$), and 5.9 MeV ($\ell_i^+ \ell_i^-$).

The beam momentum resolutions and corresponding annual integrated luminosities of the First Muon Collider have been quoted to be $\sigma_p/p = 3 \times 10^{-5}$ ($\int \mathcal{L} dt = 50\,\mathrm{pb}^{-1}$) for the narrow option at $\sqrt{s} = 100\,\mathrm{GeV}$ and 10^{-3} ($1\,\mathrm{fb}^{-1}$) at $\sqrt{s} = 200\,\mathrm{GeV}$ [1]. These correspond to beam energy spreads of $\sigma_E \simeq 2\,\mathrm{MeV}$ at 100 GeV and 150 MeV at 200 GeV. The resolution at 100 GeV is less than the expected π_T^0, $\pi_T^{0\prime}$ widths. At 200 GeV it is sufficient to resolve the ρ_T^0, but not the ω_T for the parameters we used. It is very desirable, therefore, that the 200 GeV FMC's energy spread be 10 times smaller. Since each of these technihadrons can be produced as an s-channel resonance, it would then be possible to realize most of the theoretical peak cross section. These are enormous, 2–3 orders of magnitude larger than the effective cross sections that can be achieved at hadron and linear e^+e^- colliders. To motivate an improved resolution, we shall present results for $\sigma_p/p = 10^{-3}$ and 10^{-4} at $\sqrt{s} = 200\,\mathrm{GeV}$, assuming in the latter case an annual luminosity of only $0.1\,\mathrm{fb}^{-1}$.

Like the standard Higgs boson, neutral technipions are expected to couple to $\mu^+\mu^-$ with a strength proportional to m_μ. Compared to H^0, however, this coupling is enhanced by $F_\pi/F_T = 1/\sin\chi$. This makes the FMC energy resolution well-matched to the π_T^0 width: $\Gamma(\pi_T^0)/2\delta E \gg 1$ while $\Gamma(H^0)/2\delta E \lesssim 1$ Thus, the FMC is a technipion factory. Once a neutral technipion has been found in ρ_T or ω_T decays at a hadron collider, it should be relatively easy to locate its precise position at the FMC. The cross sections for $\bar{f}f$ and gg production are isotropic; near the resonance, they are given by

$$\begin{aligned}
&\frac{d\sigma(\mu^+\mu^- \to \pi_T^0 \,\mathrm{or}\, \pi_T^{0\prime} \to \bar{f}f)}{dz} = \\
&\quad \frac{N_f}{2\pi}\left(\frac{C_\mu C_f m_\mu m_f}{F_T^2}\right)^2 \frac{s}{(s-M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,;
\end{aligned} \tag{7}$$

$$\begin{aligned}
&\frac{d\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to gg)}{dz} = \\
&\quad \frac{C_{\pi_T}}{32\pi^3}\left(\frac{C_\mu m_\mu \alpha_S N_{TC}}{F_T^2}\right)^2 \frac{s^2}{(s-M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,.
\end{aligned} \tag{8}$$

Here, $z = \cos\theta$, where θ is the center-of-mass production angle. For parameters as used below Eq. (1), the theoretical peak cross sections are $\sigma(\mu^+\mu^- \to \pi_T^0 \to \bar{b}b) = 1.4\,\mathrm{nb}$, $\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to \bar{b}b) = 0.80\,\mathrm{nb}$, and $\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to gg) = 0.25\,\mathrm{nb}$. Angular cuts and b-detection efficiencies will decrease these rates.

In Fig. 1 we show the π_T^0 and $\pi_T^{0\prime} \to \bar{b}b$ signals and γ, Z^0 background for $\delta E = 2\,\mathrm{MeV}$ and an integrated luminosity of only $25\,\mathrm{pb}^{-1}$. We have assumed $|\cos\theta| < 0.95$ and a single b-tag efficiency of 50%. The peak cross sections are 1.0 nb and 0.6 nb, respectively, over a background of 65 pb. Statistical errors only are shown. It is obvious that the widths of these resonances can be distinguished from one another. We have not considered the interesting and likely possibility of π_T^0–$\pi_T^{0\prime}$ interference. Such interferences are examined below for ρ_T and ω_T. The process $\pi_T^{0\prime} \to gg$, not shown here, has a signal to $(\bar{q}q)$ background of 250/250 pb and can be used to determine which resonance (or mixture) is being observed. Note that this channel will not show up in a heavy-flavor tag. Furthermore, we do not expect a $\bar{U}U$ technipion to decay

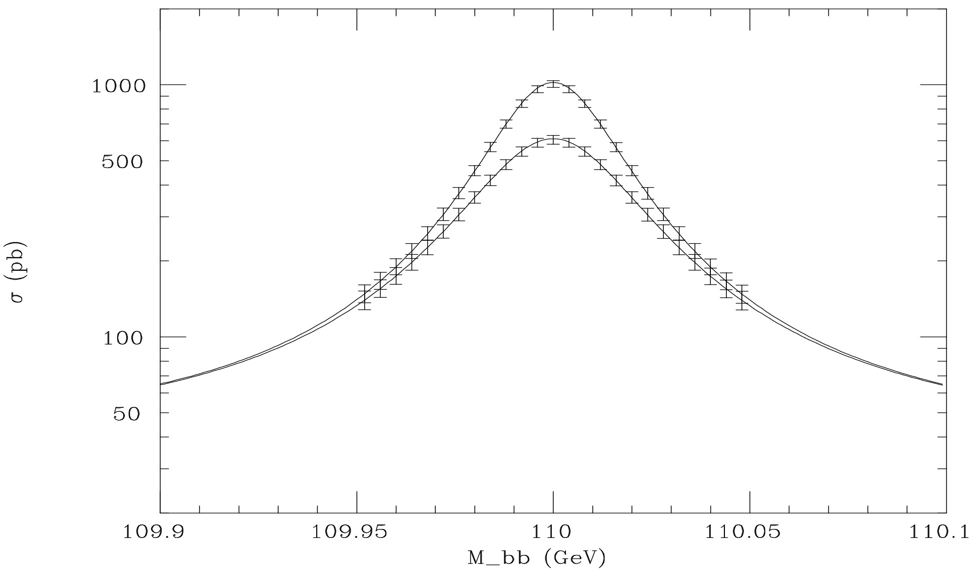

Figure 1: Cross sections for $\mu^+\mu^- \to \pi_T^0 \to \bar{b}b$ (upper curve) and $\pi_T^{0\prime} \to \bar{b}b$. Statistical errors only are shown for a luminosity of $1\,\mathrm{pb}^{-1}$ per point. Cuts and efficiencies are described in the text. The solid lines are the theoretical cross sections (perfect resolution).

to $\bar{b}b$. We conclude that the FMC can carry out very precise studies of the neutral π_T unless they are nearly degenerate with the Z^0.

A small nonzero isospin splitting between ρ_T^0 and ω_T would appear as a dramatic interference in the $\mu^+\mu^- \to \bar{f}f$ cross section *provided* the FMC energy resolution is good enough. The cross section is calculated by using the full γ–Z^0–ρ_T–ω_T propagator matrix, $\Delta(s)$. With $\mathcal{M}_V^2 = M_V^2 - i\sqrt{s}\,\Gamma_V(s)$ for $V = Z^0, \rho_T, \omega_T$, this matrix is the inverse of

$$\Delta^{-1}(s) = \begin{pmatrix} s & 0 & -sf_{\gamma\rho_T} & -sf_{\gamma\omega_T} \\ 0 & s - \mathcal{M}_Z^2 & -sf_{Z\rho_T} & -sf_{Z\omega_T} \\ -sf_{\gamma\rho_T} & -sf_{Z\rho_T} & s - \mathcal{M}_{\rho_T}^2 & 0 \\ -sf_{\gamma\omega_T} & -sf_{Z\omega_T} & 0 & s - \mathcal{M}_{\omega_T}^2 \end{pmatrix}\,. \tag{9}$$

Here, $f_{\gamma\rho_T} = \xi$, $f_{\gamma\omega_T} = \xi\,(Q_U + Q_D)$, $f_{Z\rho_T} = \xi\,\tan 2\theta_W$, and $f_{Z\omega_T} = -\xi\,\sin^2\theta_W/\sin 2\theta_W\,(Q_U + Q_D)$, where $\xi = \sqrt{\alpha/\alpha_{\rho_T}}$. The cross section is

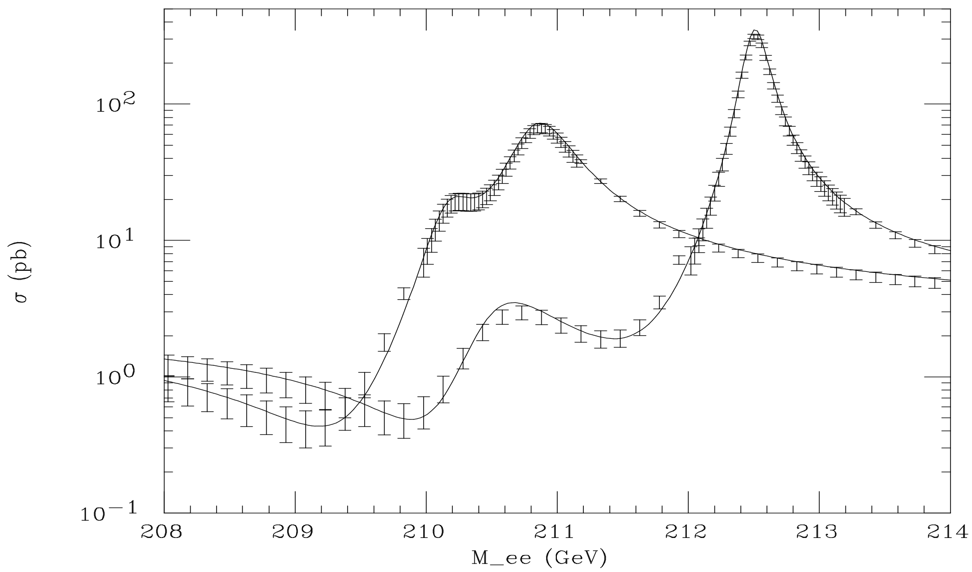

Figure 2: Cross sections for $\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 211\,\mathrm{GeV}$ (higher-peaked curve) and $209\,\mathrm{GeV}$. Statistical errors only are shown for resolutions and luminosities described in the text. The solid lines are the theoretical cross sections (perfect resolution).

given in terms of matrix elements of Δ by

$$\begin{aligned} \frac{d\sigma(\mu^+\mu^- \to \rho_T^0, \omega_T \to \bar{f}_i f_i)}{dz} &= \\ &\frac{N_f \pi \alpha^2}{8s} \left\{ \left(|\mathcal{D}_{iLL}|^2 + |\mathcal{D}_{iRR}|^2 \right) (1+z)^2 \right. \\ &\left. + \left(|\mathcal{D}_{iLR}|^2 + |\mathcal{D}_{iRL}|^2 \right) (1-z)^2 \right\} ; \end{aligned} \tag{10}$$

where

$$\begin{aligned} \mathcal{D}_{i\lambda\lambda'}(s) &= s \Big[Q_i Q_\mu \, \Delta_{\gamma\gamma}(s) + \frac{4}{\sin^2 2\theta_W} \, \zeta_{i\lambda} \, \zeta_{\mu\lambda'} \, \Delta_{ZZ}(s) \\ &\quad + \frac{2}{\sin 2\theta_W} \left(\zeta_{i\lambda} Q_\mu \Delta_{Z\gamma}(s) + Q_i \zeta_{\mu\lambda'} \Delta_{\gamma Z}(s) \right) \Big] . \end{aligned} \tag{11}$$

Figure 2 shows the interference effects in $\mu^+\mu^- \to e^+e^-$ for input masses $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 209$ and $211\,\mathrm{GeV}$. It is assumed that the resonance region (first isolated in a hadron collider) is scanned in 40 steps with a $1\,\mathrm{fb}^{-1}$ run at coarse resolution, $\delta E = 150\,\mathrm{MeV}$. The resonances are then studied with $\delta E = 15\,\mathrm{MeV}$ in a $100\,\mathrm{pb}^{-1}$ run with forty $30\,\mathrm{MeV}$ wide steps. As before, $|\cos\theta| < 0.95$. Because of the precise FMC beam energies, this is just a counting experiment and does not require excellent $e^\pm$ energy measurement. The same applies to $\bar{q}q$ final states. The effect of changing the ρ_T–ω_T mass difference by 2 GeV is striking. In both cases shown, the ρ_T is the broader structure peaking near $210.8\,\mathrm{GeV}$. For input $M_{\omega_T} = 209\,\mathrm{GeV}$, the narrow resolution picks ω_T out as the flat shoulder at $210.2\,\mathrm{GeV}$. The dip is a somewhat more pronounced in $\bar{q}q$ final states. For input $M_{\omega_T} = 211\,\mathrm{GeV}$, narrow resolution reveals a majestic peak at $212.5\,\mathrm{GeV}$ with $\sigma(\mu^+\mu^- \to e^+e^-) = 325\,\mathrm{pb}$. This demonstrates the importance of precise resolution in the 200 GeV muon collider.

Large cross sections such as these, plus the ability to measure $e^\pm$ charges, make possible detailed angular distribution measurements. These will be even more incisive if the muon beams can be polarized without great loss in luminosity. These features of the FMC will be essential for studying the charges and isospins that appear in Eqs. (4) and (6).

Before closing, we mention that associated production of technipions with weak bosons also occurs at very large rates (see Ref. [4] for the cross section formulae). For the parameters used above, $\sigma(\mu^+\mu^- \to \rho_T^0 \to W_L^\pm \pi_T^\mp) = 0.9\,\mathrm{nb}$ and $\sigma(\mu^+\mu^- \to \omega_T \to \gamma\pi_T^0) = 8.9\,\mathrm{nb}$. This offers an unparalleled opportunity to study charged technipion decay processes in a relatively clean setting.

To sum up: modern technicolor models predict narrow neutral technihadrons, π_T, ρ_T and ω_T. These states would appear as spectacular, high-rate resonances in a $\mu^+\mu^-$ collider with $\sqrt{s} = 100$–$200\,\mathrm{GeV}$ and energy resolution $\sigma_E/E \lesssim 10^{-4}$. This is a very strong physics motivation for building the First Muon Collider.

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